Extended Measurements in Bering Strait
Final Report

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LONG-TERM GOALS

Our long-term research goals are to understand the circulation and physical properties of the high-latitude ocean, both quantitatively and mechanistically, and to do so in a global context. We also seek to understand the effects of physical processes in the ocean on the ice cover, biology, and chemistry of the marine environment. The variability of that environment is a special focus and concern.

OBJECTIVES

Recent years have seen a remarkable growth in interest in the flow through Bering Strait. Rather than simply being a subject of local or regional importance, the northward flow of Pacific waters into the Arctic Ocean is now viewed as an essential part of the global ocean circulation, with pronounced consequences for global climate [cf., *Hu and Meehl*, 2005 for a recent example]. Much of this interest arises because the Pacific influx through Bering Strait is a first-order component of the global freshwater cycle [*Wijffels et al.*, 1992], and the influx is therefore critical to the ocean overturning and its large-scale circulation [*Huang and Schmitt*, 1993; *Weijer et al.*, 2001; *Hasumi*, 2002; *Wadley and Bigg*, 2002; *DeBoer and Nof*, 2004]. Beyond this, biogeochemical effects of the Bering Strait inflow are visible well into the North Atlantic [*Jones et al.*, 2003], thereby illuminating such global issues as nitrogen cycling. Within the Arctic Ocean, a particularly important dynamical aspect of the Pacific inflow is its contribution to stabilizing the upper ocean, thereby influencing vertical heat flux and ice thickness [*Aagaard et al.*, 1981; *Killworth and Smith*, 1984; *Aagaard and Carmack*, 1989; *Woodgate et al.*, 2006]. Our immediate objective under the present ONR grant was to make sustained and direct measurements of velocity, temperature, and salinity in Bering Strait, supplemented by time series of ice thickness and other properties. This upstream information has proven vital to the Shelf-Basin Interaction (SBI) initiative, since the influx of Pacific waters provides a key forcing for the western Arctic shelf-slope-basin system, including its biogeochemistry [*Walsh et al.*, 1997].

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APPROACH

Under this grant, we have maintained instrumented moorings in Bering Strait from 1999-2005. In conjunction with earlier measurements, the data provide nearly continuous records of flow and water properties in the strait since 1990. The moorings have been replaced annually during cruises that also afforded additional sampling opportunities. Velocity, temperature, and salinity have been the core physical measurements at each mooring, and these have been supplemented by shipborne hydrographic and ADCP sections within Bering Strait and over the southern Chukchi Sea. At the request of other investigators, we have incorporated additional instruments into our moorings. These additions have resulted in extensive ice thickness measurements using upward-looking sonar, *in situ* nutrient determinations, and time series of optical properties, especially those related to primary production.

During the early 1990s, we were able to maintain a mooring in both the western and eastern channels of Bering Strait (designated A1 and A2, respectively). The western channel is within the Russian Exclusive Economic Zone (EEZ), however, thus requiring special permission to work there. After our initial success in deploying in the western channel [*Roach et al.*, 1995], we were unable to secure permission to continue the measurements. We therefore had to rely on an additional mooring emplaced north of the Diomede islands, just east of the Russian EEZ. This northern mooring (designated A3) has served as a proxy monitor of the western channel, since it lies in the path of a portion of the flow through the western channel that veers to the northeast immediately after passing the Diomedes, following the bathymetric trend [*Roach et al.*, 1995; *Woodgate et al.*, 2005a; b]. Recently, a NOAA-sponsored effort to again open the entire strait to scientific investigation has been successful, resulting in the western once more being instrumented in a Russian-American collaborative venture. A further expansion of the Bering Strait array occurred during the ONR grant period reported here, when we added a mooring in the eastern channel (designated A4) within the fast, low-salinity coastal flow (**Figure 1**). This new instrumentation has proven to be an important addition to the Bering Strait array, and it has resulted in considerably improved estimates of the freshwater and heat transports though the strait [*Woodgate and Aagaard*, 2005; *Woodgate et al.*, 2005b; 2006].

Together with the extensive shipborne measurements made each year, our instrumented array has provided unique information on the temporal and spatial variability of the flow and water properties in Bering Strait, as well as supplying the data for greatly improved estimates of freshwater and heat fluxes and their uncertainties.

A considerable effort has also been made to analyze and synthesize these data. Emphases in our analysis have included the contribution of the Bering Strait throughflow to the Arctic freshwater budget [*Woodgate and Aagaard*, 2005; *Aagaard et al.*, 2006; *Serreze et al.*, 2006]; the forcing of the variable flow through the strait, including wind and sea level effects [*Aagaard et al.*, 2006; *Woodgate et al.*, 2006]; and the control of the throughflow salinity [*Aagaard et al.*, 2006; *Danielson et al.*, 2006]. We note that in turn the salinity in the strait substantially determines the density of the Pacific waters in the northern Chukchi Sea, where these waters are mixed and subsequently ventilate the Arctic Ocean halocline [*Weingartner et al.*, 2005; *Woodgate et al.*, 2005c]. The various analyses done under this grant have substantially illuminated dynamical questions raised in earlier studies [e.g., *Coachman and Aagaard*, 1966; *Coachman et al.*, 1975; *Overland and Roach*, 1987; *Spaulding et al.*, 1987].

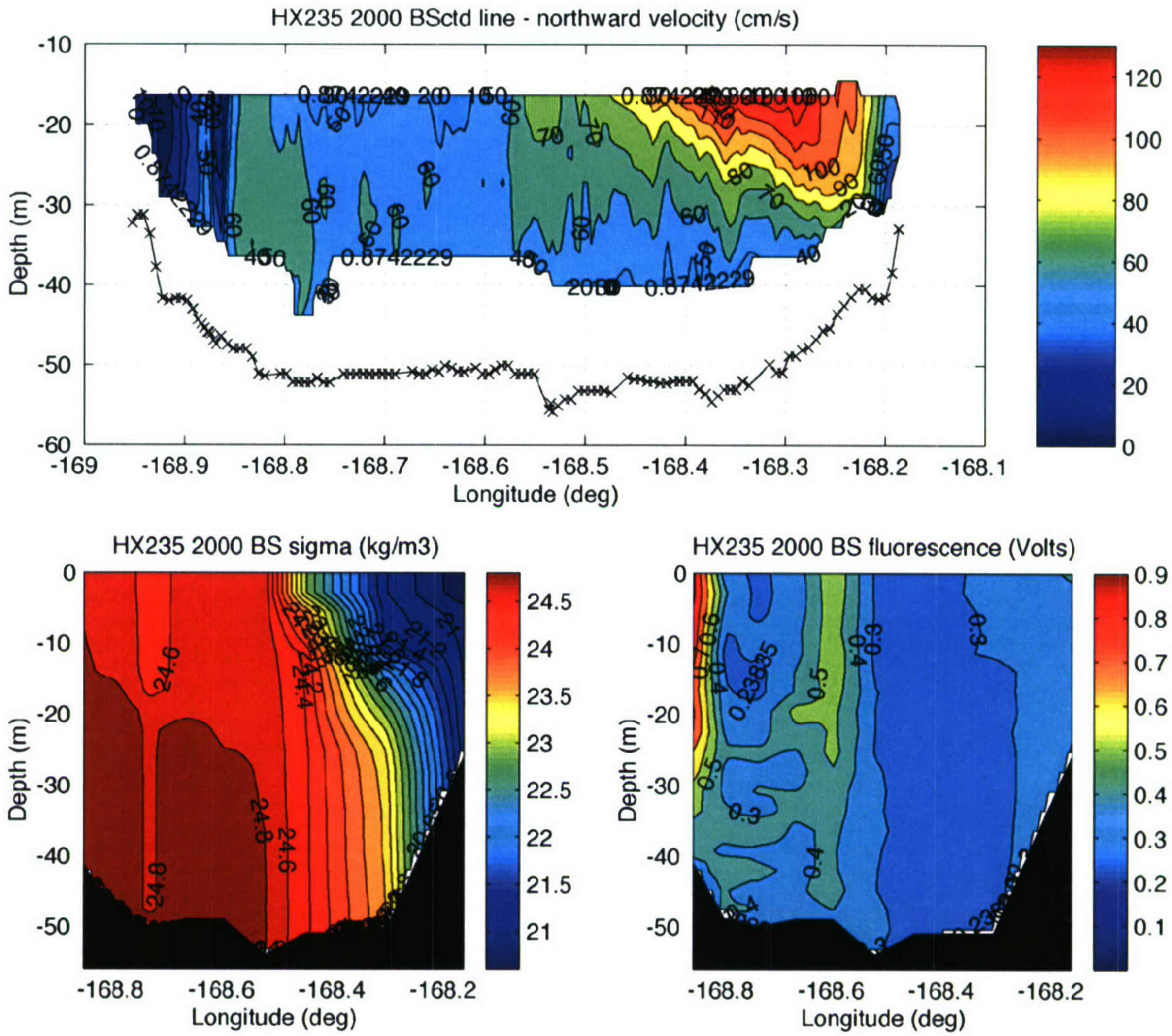

Figure 1: ADCP (top), density (lower left), and fluorescence (lower right) sections across the eastern channel of Bering Strait, August 2000. These sections show a strong surface-intensified jet on the eastern side of the strait in summer, with speeds twice that of the ambient flow. The jet coincides with the sharp density gradient over the base of the steepest topography, inshore from the mid-channel mooring location. These observations led us add another mooring (A4) at the location of the jet. Note in the fluorescence section that a large increase is visible on the western side, just east of Little Diomede Island. This is a signature of the high primary production within the water being carried northward through the western channel of the strait, which we monitor with mooring A3.

WORK COMPLETED

The ONR-sponsored work under this project includes seven cruises in Bering Strait and the Chukchi Sea during 1999-2005. Field work did not end in 2005, however, since continuing measurements in Bering Strait are being funded by other agencies, building on the earlier efforts. The ONR grant has therefore been pivotal not only in contributing to nearly continuous coverage of an ocean passage critical to understanding the history of the global ocean, and of its present and future state, but also in stimulating and encouraging other programs to build and extend observational coverage of the strait.

The entire moored data set from 1990-2005, together with the extensive shipborne measurements, have been processed and submitted to JOSS/EOL for archiving, as designated by the SBI program. The data are also archived at our web site (http://psc.apl.washington.edu/BeringStrait.html).

Our analysis efforts under this grant have resulted in six papers published in the *Journal of Geophysical Research* and *Geophysical Research Letters*, and in 11 presentations at national and international meetings. We discuss the principal scientific results below.

RESULTS

The freshwater flux through the Bering Strait into the Arctic Ocean is important both regionally and globally, e.g. to the hydrography and circulation on the vast Chukchi shelf [*Coachman et al.*, 1975; *Coachman and Aagaard*, 1981; *Weingartner et al.*, 2005; *Woodgate et al.*, 2005a], to the stratification of the Arctic Ocean [*Aagaard et al.*, 1981; *Aagaard and Carmack*, 1989], to the global freshwater cycle [*Wijffels et al.*, 1992], and to the stability of the Atlantic overturning circulation [*Goosse et al.*, 1997; *DeBoer and Nof*, 2004]. In an earlier study based on far more limited data, *Aagaard and Carmack* [1989] estimated the Bering Strait freshwater flux as 1670 km^3/yr (relative to 34.8 psu), assuming an annual mean transport of 0.8 Sv and a mean salinity of 32.5 psu. This flux is about one-third of the total freshwater input to the Arctic Ocean. Using our new long-term moored measurements through the 2004 field season, along with ship-based observations, we have re-examined the freshwater flux through Bering Strait (**Figure 2**) [*Woodgate and Aagaard*, 2005]. We have paid special attention to the effects of stratification, ice flux, and the coastal jet in the eastern part of the strait. We find that the earlier results of *Aagaard and Carmack* [1989] substantially underestimate the freshwater flux through the strait. In particular, the warm, fresh Alaskan Coastal

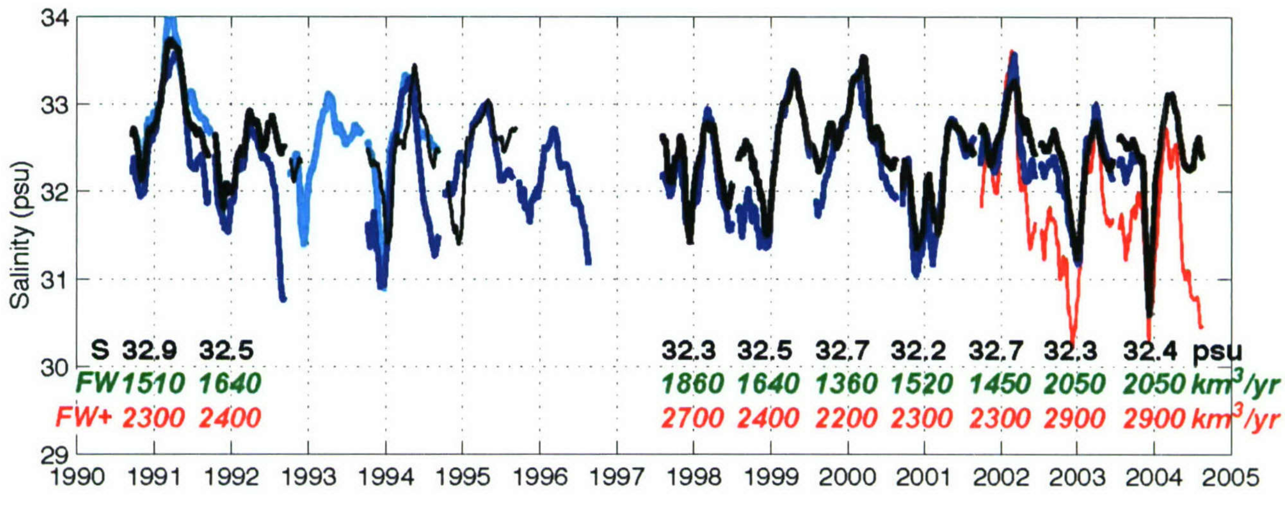

Figure 2: Thirty-day running mean of hourly time-series of salinity 9 m above bottom at sites A1 (western channel, cyan), A2 (eastern channel, blue), A3 (north of Bering Strait, black), and A4 (the Alaskan Coastal Current, red). Not all moorings are deployed each year. Between summer 1992 and summer 1995, A3' (thin black line) was deployed 200 km north of the A3 position. Record annual mean salinities, i.e., annual mean from summer to summer (S, black, with errors ~ 0.2 psu), and freshwater transports (errors ~ 300 km^3/yr) are estimated from the A3 records, assuming no stratification in velocity or density (FW, green) and with the correction of 800 km^3/yr (FW+, red).

Current in eastern Bering Strait likely adds ~ 400 km^3/yr to the total freshwater transport, while corrections associated with seasonal stratification and with ice flux may add another ~ 400 km^3/yr. Our new freshwater flux estimate is therefore ~2500 km^3/yr (0.08 Sv), some 50% larger than that of *Aagaard and Carmack* [1989]. The uncertainty is ~ ± 300 km^3/yr (0.01 Sv). Our new estimate places the Bering Strait freshwater transport as ~75% of the *Aagaard and Carmack* [1989] estimate of river runoff into the Arctic Ocean, and fully comparable to their estimate of ice export through Fram Strait. Combined, the flux corrections are larger than the interannual variability observed by near-bottom measurements. Near-surface measurements will therefore be necessary if our new estimates of the freshwater flux through Bering Strait and its interannual variability are to be substantially further improved.

A realistic assessment of Bering Strait throughflow properties is also necessary for model validation and for providing boundary conditions of high-resolution ocean models. From 14 years of moored measurements, we have therefore constructed a monthly climatology of temperature and salinity (**Figure 3**) and of transport (**Figure 4**) [*Woodgate et al.*, 2005b]. The strong seasonality in all properties (~ 31.9 to 33 psu, ~ -1.8 to 2.3°C, and ~ 0.4 to 1.2 Sv) dominates the Chukchi Sea hydrography and implies significant seasonal variability in the equilibrium depth and ventilation properties of Pacific waters in the Arctic Ocean. Interannual variability is large in both temperature and salinity. Although missing some significant events, an empirical linear fit to a modeled local wind yields a reasonable reconstruction of the water velocity, and we have used the coefficients of this fit to estimate the magnitude of the Pacific-Arctic pressure head forcing of the Bering Strait throughflow.

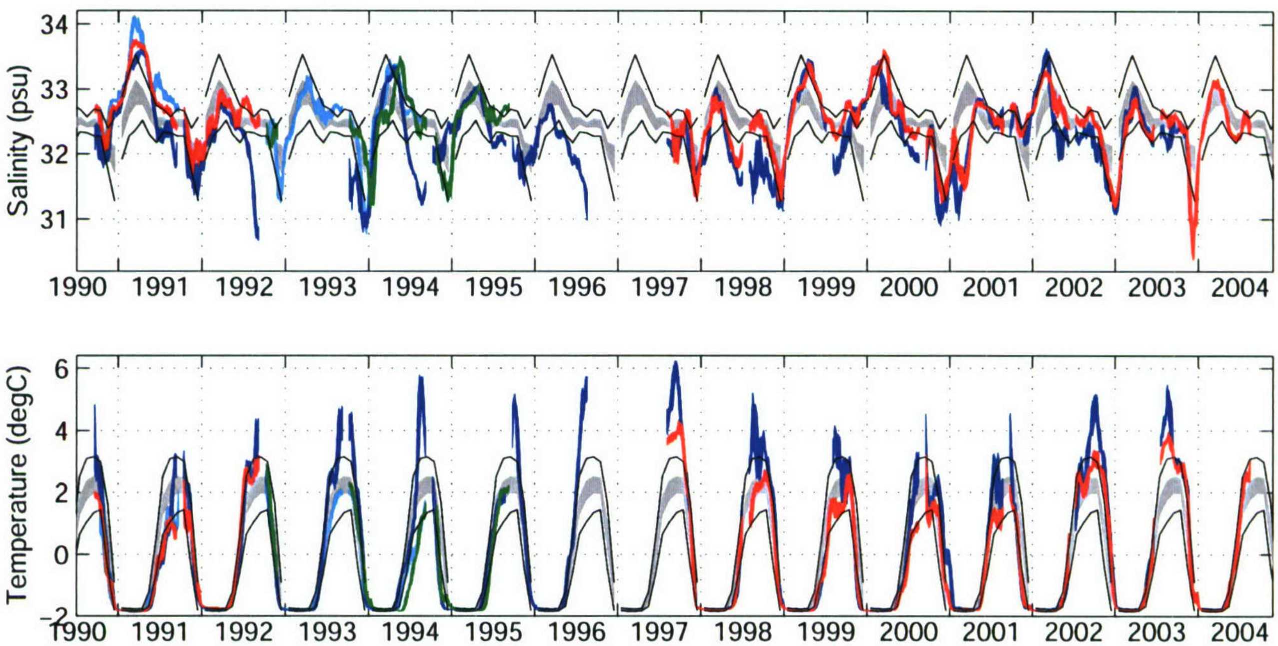

Figure 3: Fourteen year 30-day smoothed time series of salinity (top) and temperature (bottom) from ~ 9 m above bottom at mooring A1 in the western channel of Bering Strait (cyan); at A2 in the eastern channel (blue); at A3 immediately north of the Diomede Islands, which captures flow through both channels (red); and at A3' about 200 km north of the strait (green, summer 1992 to summer 1995). Line width indicates errors. Grey area and black lines are the full record length climatology. Water column means are probably ~ 0.5 to 1 psu fresher and 1 to 2°C warmer than these near-bottom values during summer/autumn.

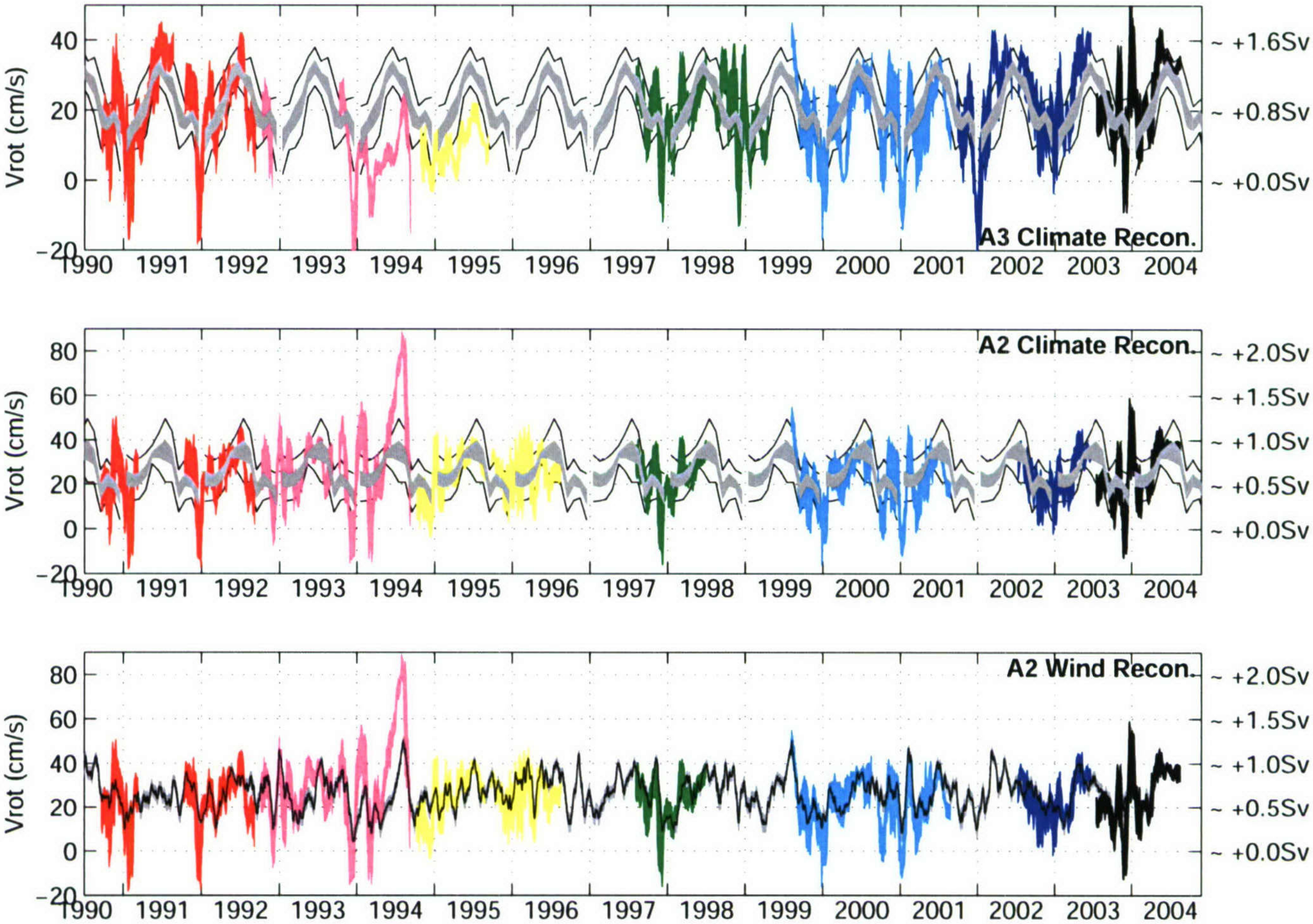

Figure 4: Fourteen year 30-day smoothed time series of the principal component of velocity (top) at A3 and A3' (true heading 329°) and (middle and bottom) at A2 (true heading 0°). Velocity climatologies from A3 and A2 (with errors and standard deviation) are marked in the top and middle panels. Data from A3' are not included in the climatology. The thin black line in the bottom panel marks the 30-day smoothed reconstruction of velocity from a linear fit to the NCEP 6-hourly winds, i.e., reconstructed velocity (cm/s) = 32 + 3.4 x NCEP 10 m wind component (m/s) at heading of 330°. Coefficients are obtained from a least squares fit [cf., Woodgate et al., 2005a]. Gray in this panel indicates errors in the coefficients. Conversions to transports (using cross-section areas of ~ 2.6 km^2 at the A2 latitude and ~ 3.9 km^2 at A3) are marked on the right-hand axis. These transports are subject to ~ 20% errors in addition to those indicated by the error bars in the individual mooring plots.

In another recent study supported by this grant, we have examined both the large-scale forcing of the Bering Strait throughflow and the principal processes by which the mean salinity in the strait is controlled [*Aagaard et al.*, 2006]. During 1993–1994, steric forcing of flow through Bering Strait represented a northward sea level drop of ~0.7 m from the Bering Sea Basin to the adjacent deep Arctic Ocean, of which ~2/3 was due to the salinity difference between the basins. Seasonal variability of steric forcing appears small (<0.05 m), in contrast to large seasonal wind effects. Interannual changes in steric forcing may exceed 20%, however, and warm inflow to the Arctic Ocean from the

North Atlantic, accumulation of freshwater in the southwest Canada Basin, and temperature and salinity changes in the upper Bering Sea have all contributed to recent changes in steric forcing through the strait. The mean salinity balance in Bering Strait is primarily maintained by large runoff to the Bering shelf, dilute coastal inflow from the Gulf of Alaska, and on-shelf movement of saline and nutrient-rich oceanic waters from the Bering Sea Basin (**Figure 5**). In Bering Strait, therefore, both the throughflow and its salinity are affected by remote events.

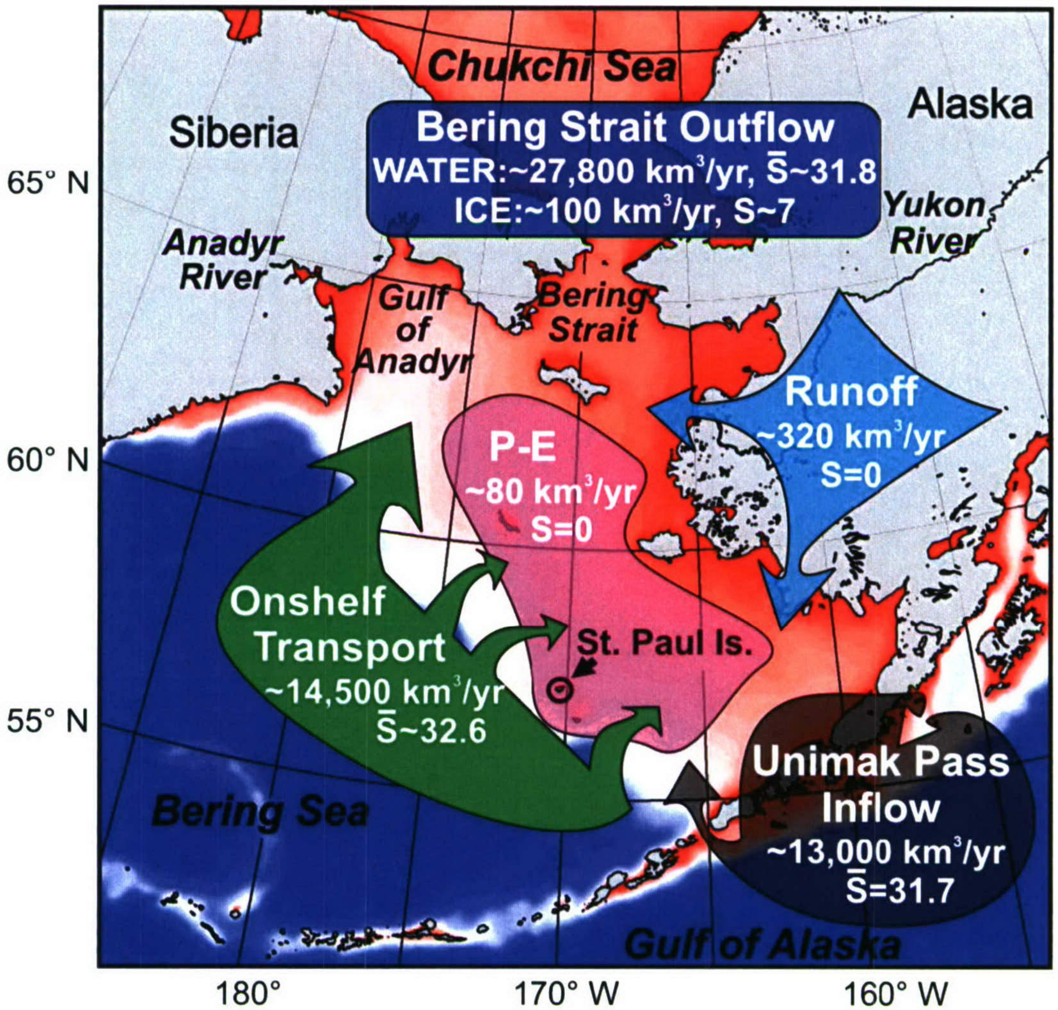

Figure 5: Schematic of the Bering shelf water and salt budgets. Precipitation, evaporation, and salinity are denoted P, E, and S, respectively. Onshelf flow from the deep Bering Sea and inflow from the Gulf of Alaska through Unimak Pass are approximately equal, and together they dominate the mass balance in Bering Strait. The salt balance in the strait is primarily maintained by the different salinities of these two flows, together with freshwater runoff directly onto the Bering shelf.

On the basis of our moored records during 1990-2004, we have also directly examined the interannual variability of the fluxes of volume, freshwater, and heat through Bering Strait (**Figure 6**) [*Woodgate et al.*, 2006]. These fluxes were lowest in 2001 and then increased rapidly, so that by 2004 the volume and freshwater fluxes matched the previous high reached in 1998, while the heat flux was the largest

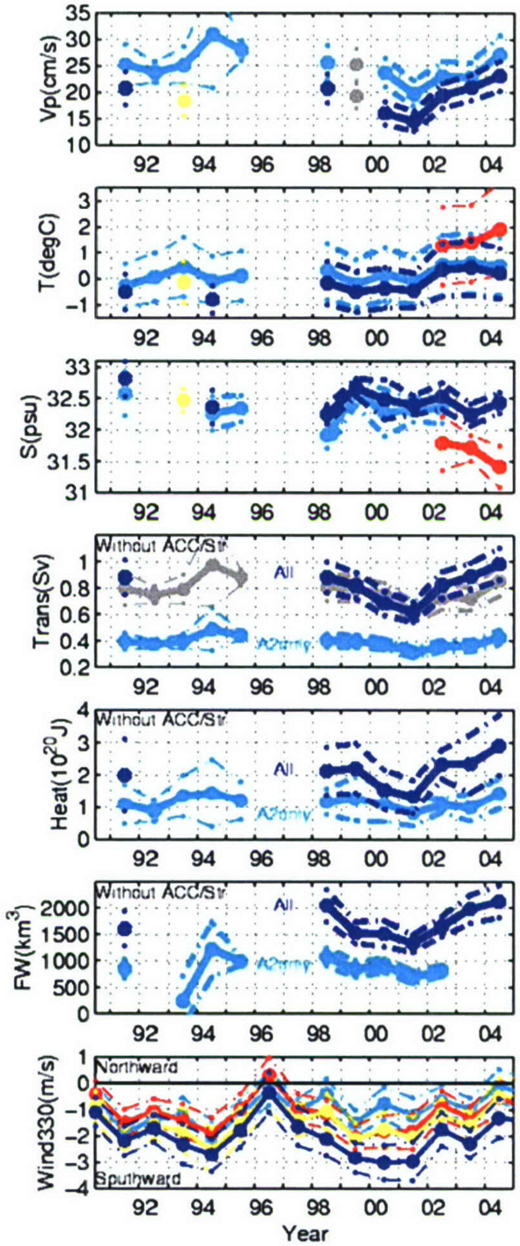

Figure 6: Annual means of near-bottom principal component (~ northward) of velocity (Vp), temperature (T), and salinity (S) in Bering Strait (panels 1-3); estimates of volume transport, heat flux, and freshwater flux through the strait (panels 4-6); and annual mean NCEP wind toward 330°T at four locations north or south of the strait (bottom panel). For the top three panels, yellow indicates the western channel of the strait; cyan the eastern channel; blue a site just north of the strait that embodies characteristics of both channels; and red the portion of the eastern channel near the Alaska coast, which is occupied by the Alaska Coastal Current (ACC). For transport and flux estimates (panels 3-6), blue represents the entire strait and cyan the eastern channel only. For transport, the gray line is the entire strait transport as estimated from measurements in the eastern channel only. Corrections for stratification and enhanced fluxes in the ACC (not included) are ~ 1 - 2x10^{20} J/yr (heat) and 800 - 1000 km^3/yr (freshwater). Dashed lines indicate estimated errors in the means. Grey dots in Vp indicate results from partial years (used for flux estimates). In the bottom panel, blue and red are north of the strait, cyan and yellow are south.

recorded, the latter in part due to the very high temperatures after 2002. The Alaska Coastal Current, occupying the easternmost part of the strait and responsible for about one-third the heat flux through the strait and one-fourth the freshwater flux, showed a particularly strong warming and freshening between 2002-2004. The increased heat flux through Bering Strait between 2001 and 2004 ($>2 \times 10^{20}$ J) is sufficient to melt 640,000 km^2 of ice 1 m thick; while the freshwater flux increase during the same period (~800 km^3) is about one-fourth the annual runoff to the Arctic Ocean. Weaker northerly winds during this period likely explain much of the increase in volume flux that in turn accounts for about 80% of the increase in freshwater flux and 50% of that of heat.

IMPACT/APPLICATIONS

Major goals of the SBI initiative are to understand the physical processes responsible for water mass modification over the arctic shelves and slopes, and for exchanges with the interior ocean, as well as to understand the variability of this system. Our reported project has addressed these goals directly. In particular, we have quantified the large variability found in the Pacific-origin waters that flush the western Arctic shelves, and we have illuminated the origin of this variability. Much of the variability is generated in the Bering Sea, since our measurements suggest that the salinity of at least the lower water column is not greatly altered during its transit of the Chukchi shelf [*Woodgate et al.*, 2005a], although in some years the northward-flowing waters may be further modified in the Chukchi Sea, particularly along the Alaskan coast during winters with extensive open water [*Aagaard et al.*, 1985; *Weingartner et al.*, 2005]. The winter salinity increase on the shelf results in part from intensive ice formation in coastal polynyas (cf., **Figures 7** and **8** for an example from the northern Bering shelf) and in part from freezing distributed widely over the shelf [*Aagaard et al.*, 1981; *Schumacher et al.*, 1983; *Cavalieri and Martin*, 1994; *Danielson et al.*, 2006].

Eventually these shelf waters are discharged into the Arctic Ocean, where their seasonal and interannual variability are propagated long distances, in part by long-lived eddies that drift into the interior [*Newton et al.*, 1974; *Manley and Hunkins*, 1985; *D'Asaro*, 1988; *Muench et al.*, 2000], in part by topographically steered boundary currents that rim both the Polar Basin and its major ridge structures [*Aagaard*, 1989; *Rudels et al.*, 1994; *McLaughlin et al.*, 1996], and in part by other features of the circulation [e.g., *Carmack et al.*, 1997; *Smith et al.*, 1999. This propagation leads to variability in regions far from the originating shelves [cf., *Swift et al.*, 1997 and *Woodgate et al.*, 2001 for examples]. An understanding of these effects and processes is vital to realistically modeling the Arctic Ocean and its global connections [*Huang and Schmitt*, 1993; *Wadley and Bigg*, 2002; *DeBoer and Nof*, 2004; *Peterson et al.*, 2006]. The work accomplished under the grant reported here has contributed to this complex undertaking.

The accumulated time series from Bering Strait, now over a decade-and-a-half long, provide a remarkable record of the upstream forcing of the Chukchi shelf, and thereby contribute to understanding the ventilation history of the Arctic Ocean halocline. We note that the very high salinities at the beginning of the 1990s have not returned to Bering Strait since. Rather, recent years have seen an alteration between fresh and moderately saline regimes, but with a marked freshening after 2001 [*Woodgate et al.*, 2006]. Therefore, for ventilation of the Arctic Ocean halocline to again be as deep as it may have been in the early 1990s, when the Bering Strait winter waters were exceptionally saline, there would either have to be extensive freezing downstream on the eastern Chukchi shelf, something which in turn depends on fall and winter ice and wind conditions in the

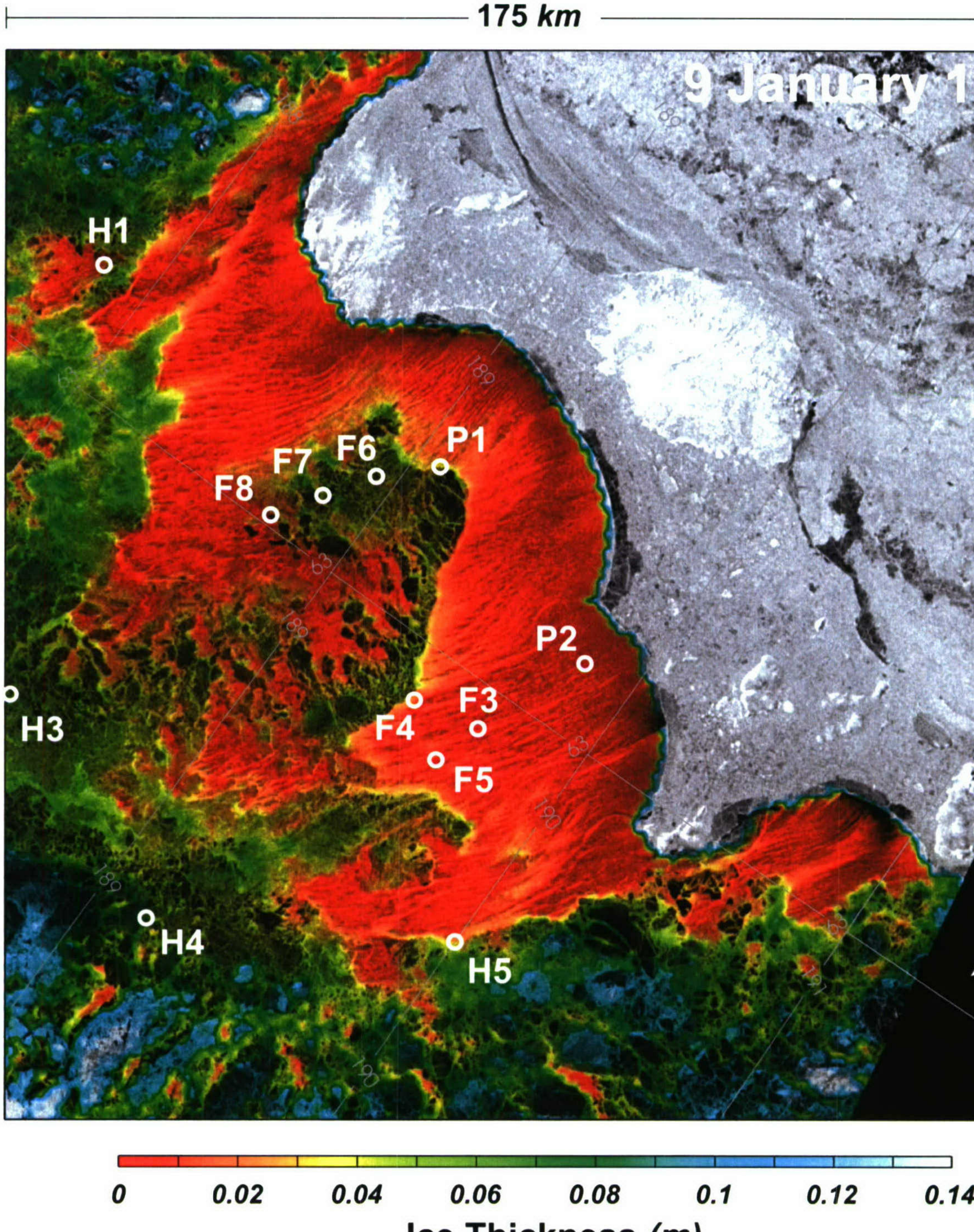

Figure 7: Composite SAR and AVHRR image of the St. Lawrence Island polynya on 9 January 1999, adapted from Drucker et al. [2003]. The region within the polynya is strongly wind-driven, with wind and waves forcing the frazil ice into long linear streaks characteristic of Langmuir circulation. Mooring locations [Danielson et al., 2006] are plotted in white. SAR images copyright 1999 by the Canadian Space Agency.

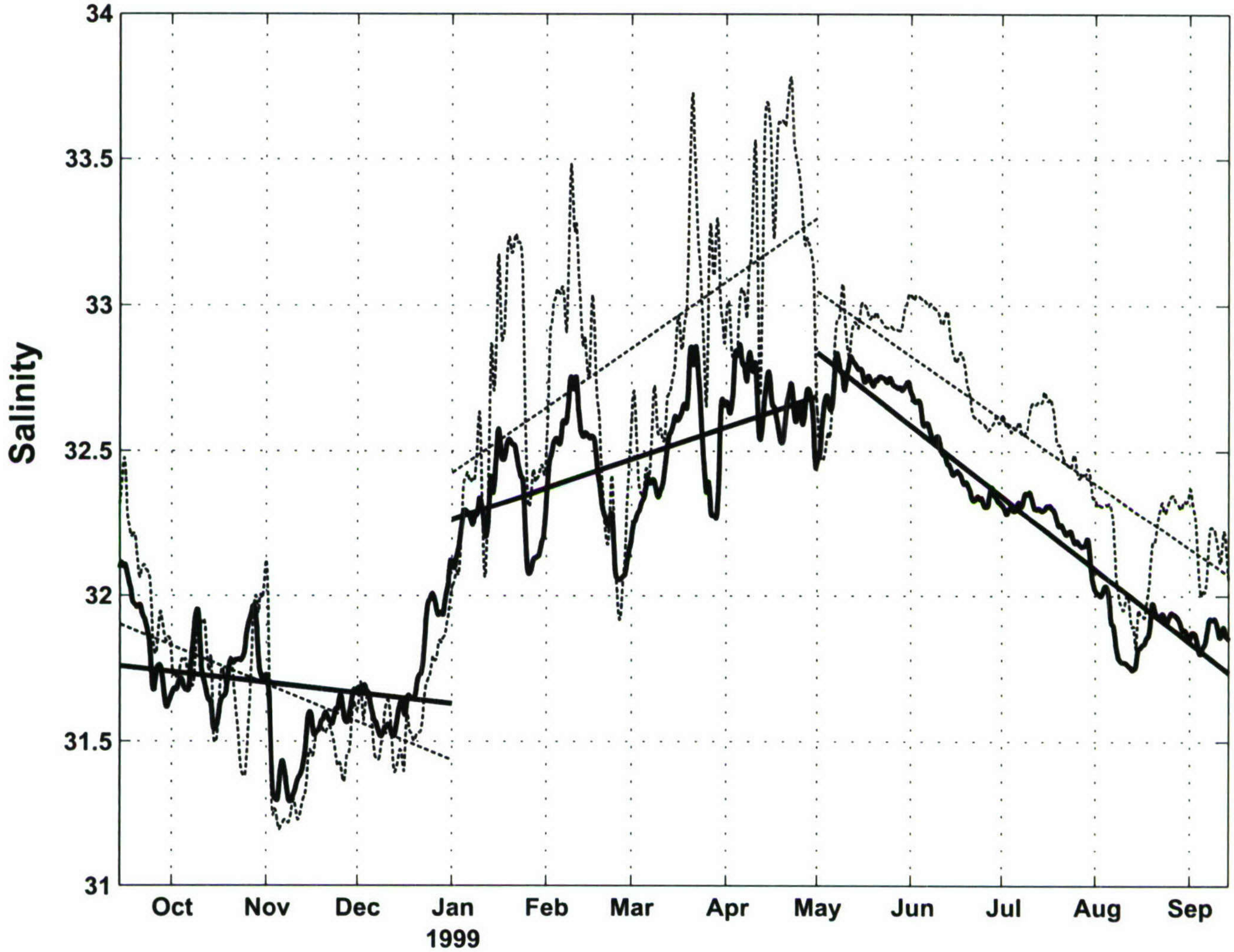

Figure 8: Mean spatially interpolated salinity over the entire St. Lawrence polynya moored array shown in Figure 7 (solid line) and over the F3-F4-F5 triangular sub-array (dashed line) during September 1998-September 1999. The full array compilation represents ~6500 km^2, and the subarray represents ~41 km^2. The straight lines are the seasonal salinity trends for each array. Comparison of these trends with ice formation rates calculated from the surface heat budget suggests that about half the salinization tendency due to freezing is offset by an advective freshening tendency. The latter results in part from import of low-salinity Alaskan coastal waters carried offshore by the shelf circulation and in part from export of brine-enriched waters northward through Bering Strait.

Chukchi Sea [*Weingartner et al.*, 2005], or a change in the mixing regime over the Chukchi slope [*Woodgate et al.*, 2005a; c]. With respect to temperature, the pronounced warming after 2002 has brought temperatures in the eastern channel close to the peak reached in 1997 [*Woodgate et al.*, 2006].

We have also found evidence for interannual changes in the steric sea level difference that likely provides the major forcing for the northward flow through Bering Strait. Our analysis of profiling float data and shipborne measurements suggests a decrease in steric height difference between the deep northern Bering Sea and the adjacent Arctic Ocean of ~20 % between 1993–1994 and the early part of the present decade, due almost equally to an increase in steric height in the Arctic Ocean because of warming and freshening, and a decrease in the Bering Sea due to salinization. During 2001–2006, however, the steric height in the Bering Sea was again increasing as the upper ocean warmed and freshened. While these various indications are fragmentary, taken together they suggest significant interannual variability in steric height both in the Bering Sea and in the adjacent Arctic Ocean, and that the variability in one basin is largely independent of that in the other, resulting in a variable regional sea level slope. The steric height increase in the Arctic Ocean between 1994 and 2002 resulted from advection of warm water from the North Atlantic, together with a regional change in the freshwater distribution, while the steric height decrease in the Bering Sea during about the same period was driven by a change in the salt budget. The variable steric forcing for the Bering Strait was therefore remotely controlled from as far away as the North Atlantic.

RELATED PROJECTS

In Bering Strait we have worked cooperatively with T. Whitledge and T. Weingartner, UAF, including deployment of *in situ* nitrate and optical sensors (transmissivity, fluorescence, PAR). These measurements are representative of the new techniques that will be required to illuminate biogeochemical cycles in the high-latitude ocean. We have also cooperated with R. Moritz, UW, through deployment of upward-looking sonars to measure ice thickness. These deployments address the need for circumpolar time series measurements of ice thickness, both to illuminate issues of ice mechanics and thermodynamics and to track ice thickness during this time of rapid change in the Arctic. Additionally, our work has variously been done in collaboration with Canadian studies in Bering Strait (E. Carmack and J. Cherniawsky, IOS; e.g., cf. *Cherniawsky et al.* [2005]), and with the RUSALCA project (J. Calder, NOAA and AARI, St. Petersburg). The latter project includes mooring work in the western channel of Bering Strait by T. Whitledge and T. Weingartner, UAF. We have also assisted a number of other investigators and students in Bering Strait by providing sampling opportunities during the mooring cruises, including samples for programs supervised by L. Cooper and J. Grebmeier.

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14. ABSTRACT
We completed seven cruises in Bering Strait and the Chukchi Sea during 1999-2005. Both the shipborne measurements and nearly continuous moored data from 1990-2005 have been processed and archived. In six refereed papers and eleven presentations at national and international meetings, we have quantified the large variability found in the Pacific-origin waters that flush the western Arctic shelves. Eventually these shelf waters are discharged into the Arctic Ocean, where their seasonal and interannual variability are propagated long distances, leading to variability in regions far from the originating shelves. An understanding of these effects and processes is vital to realistically modeling the Arctic Ocean and its global connections, and our work has contributed significantly to this complex undertaking. For example, the accumulated time series from Bering Strait, now over a decade-and-a-half long, provide a remarkable record of the upstream forcing of the Chukchi shelf, and thereby contribute to understanding the ventilation history of the Arctic Ocean halocline.

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